Design of a robotic platform for hip fracture rehabilitation in elderly people

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***Abstract*— Falls are a major cause of injury among people over 65, being the hip fracture the most common consequence. The morbidities and even the high mortality associated lead to considerable social and economic costs surrounding the rehabilitation process. Hip fracture rehabilitation is long and complex and related to advanced age. The relentless growth of the older population in developed countries has made technology pursues new challenges to improve the quality of life and independence of this population. One of the newest applications has been the development of robotic platforms to rehabilitate musculoskeletal diseases. Within this context, this paper describes the design and development of a robotic platform, called SWalker, for hip fracture rehabilitation. The main goal of the platform is to promote the early weight bearing and mobilization. The paper describes the technical and functional validation of the system with a limited number of elderly patients. The positive results coming from the users suggest that the system is reliable, and it is ready for future clinical validation.**

I. Introduction

Hip fractures in later life constitute an important health problem with severe implications on functional dependence, social and economic costs and even mortality. Due to population aging, the prevalence of hip fractures will increase strongly in the future decades [1], [2]. Several risk factors for hip fracture are associated with lifestyle conditions, such as loss of skeletal strength and low degree of physical activity. Falls are an important cause of hip fracture. About 28% of people over 65 suffer a fall per year, and the percentage is even higher in people older than 75 (about 36%) [3]. Approximately 40% of elderly people with a fracture do not recover their previous functional activity [4]. As a consequence, a notable reduction in autonomous mobility leads to an increase in mortality, especially during the first years following the fracture [5]–[7]. Indeed, in-hospital mortality varies between 4 and 8%, reaching between 25 and 30% 1 year after the admission [8]. The CHANCES project followed up 122.808 patients with hip fracture for a mean of 12.6 years in Europe and the USA. This study found a significant relation between hip fracture and excess short- and long- term mortality in both sex [9]. Clinical intervention studies indicate that daily follow-up and intensive interdisciplinary rehabilitation during hospitalization may reduce in-hospital mortality and medical complications [10]. However, these practices frequently had to be delayed because home care services or rehabilitation center facilities could not be arranged in a timely manner [11].

The use of robotic devices has increased in the last decades, especially focused on neurorehabilitation of disorders, mostly stroke, spinal cord injury, cerebral palsy or Parkinson [12]. Robotic rehabilitation presents advantages compared to conventional therapy integrating functional tasks with accurate and assembled movements instead of repetitive movements [13]. These devices propose a cost-effective method and more effective than the conventional one in reaching the patient's ability to recover walking independence, [14]. Additionally, robotic rehabilitation has greater acceptability than traditional one [15]. The most popular robots for rehabilitation are focused on improving the gait function such as Lokomat [16], Gait Trainer [17] or the wearable exoskeletons designed by Ekso Bionics [18], [19]. However, these robotic devices have not been specifically addressed for the rehabilitation of hip fractures in elderly patients.

There is a lack of robotic devices for hip fracture rehabilitation. However, extense literature supports the early weight bearing and mobilization on post-operative rehabilitation. Additionally, outcome measures on rehabilitation treatment (e.g. post-operative gait speed or sway parameters) are needed to determinate optimum rehabilitation dosage, [20]. All these aspects are usual functionalities of robotic platforms. Some robotic platforms have already been tested in populations with hip fracture, for balance control exercises and monitoring [21]. However, scientific articles testing robotic platforms specifically designed for rehabilitation of hip fracture in elderly population have not been found [22].

This paper describes the conceptual design, technical development and functional validation of a robotic platform, called SWalker. The main functional goal of the SWalker is to facilitate the early mobilization and ambulation using a safety walker frame. The early intervention will pursue to reduce the high morbidity and increase the independence after the therapy. SWalker is partial body weight-supported walker and traction power. Besides of the actuators to provide those functions, it incorporates a set of sensors to measure the weight supported and gait speed. The technical challenge is to combine all these components in a safe and

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usable system working in a real rehabilitation scenario. The design shares some of the most technical aspects of robotic devices in literature, but including relevant modifications for the target population.

The next section illustrates the conceptual design of the SWalker. Section III describes the modules of the system, mechanical structure, sensors, actuators, control unit and graphical therapist interface. Section IV describes the interoperability protocols between the different modules. Section V describes the technical and functional validation at Albertia facilities. Finally, the last section presents the discussion, the conclusions and the future work.

II. Design concept

SWalker project aims to create a safety and usable framework for hip fracture rehabilitation in elderly population. The conceptual design collects the three key functionalities for the rehabilitation process: 1) Being safe and usable to reach user's acceptance; 2) Facilitating early weight bearing and mobilization; and 3) Monitoring variables to determinate rehabilitation dosage and progress.

The paramount aspects are the safety and stability of the system. The patients' perception of their own capacity to recover pre-facture function is generally heterogeneous and strongly dependent on cognitive skills. Therefore, usability and user's perception of the robotic device must be also considered. In particular, the design of the transfer procedure from wheelchair to the SWalker must be particularly analyzed. From the physical point of view, the target population has limited range of motion and strength in their lower limbs. Therefore, they have reduced capability to move naturally following standard gait patterns, balance or motor coordination [22], [23], [25]. Some degree of weight bearing is very important to activate anatomical structures responsible for bone healing. A partial body-weight support system is useful to modulate that degree of weight bearing.

The robotic device will be designed according to these three functionalities. The walker frame consists of a mechanical mechanism to body-weight support and motorized traction. The user's stability is achieved by two adjustable parallel bars and an adaptable trunk harness (see Fig 1). Several sensors are also included to provide relevant outcome measures, concretely, hip range of motion, weight supported by the robot and gait speed. The Swalker incorporates a control unit to capture the information from the sensors and control the actuators accordingly. Finally, a graphical therapist interface, running on a conventional tablet, is designed to control the Swalker and monitor the parameters. This interface includes a patients' database with all the information about the therapy sessions.

III. Mechanical structure

The mechanical assembly was designed to guarantee a proper function for individuals with a maximum height of 180 cm and 90 kg of weight. The structure is robust, manufactured in aluminum and steel (the parts subjected to greater mechanical stress). The structure consists of a T-shaped frame supported on four wheels. Two adjustable parallel grab bars are integrated on the robot frame to increase the patient's comfort and safety perception. These bars are similar to those used during conventional rehabilitation therapies. The familiar appearance contributes to the patient's acceptance.

Figure 1. General view of the SWalker robotic platform

During the transfer process (from wheelchair or conventional walker to Swalker) the T-shaped structure with the parallels bars are extracted and the SWalker is approached to the patient. Then, the harness and the thigh straps are adjusted. Finally, the T-shaped structure and parallels bars are re-installed.The mechanical frame consists of the three following modules:

A. *Drive system*

Two gear motors (Kelvin K80 63.105) equipped with encoders are coupled to the back wheels (Fig. 2). The encoders provide speed information used in a proportional-integrative-derivative (PID) closed-loop to adjust speed, not depending on patient's weight or ground surface. The maximum speed of Swalker is 0.6 m/s, which was established by the clinical therapists according to the standard rehabilitation program.

B. *User's body weight support system*

This system is composed by two cylinder-piston actuators, vertically positioned (E21BX300-U-001, Bansbach easylift, Germany) activated by a hydraulic pump, which is controlled by an electric motor. The mechanism consists of a rail system to elevate a rigid structure in which the patient's hip is properly tightened. The mechanical parts were designed to range weight discharge from 0% (patient is fully suspended) to 100% (user is completely on the floor).

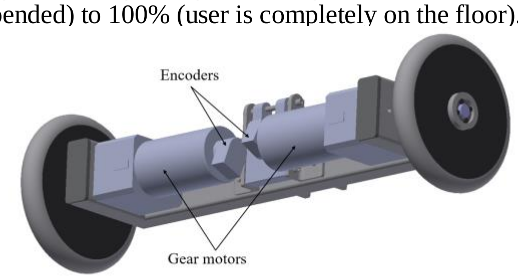

Figure 2. Drive System. Two gear motors equipped with encoders provide the traction function of the system.

This system measures the amount of weight supported by means of a load cell (type FT1 code CFT1350KC25, REP transducers, Italy). This information allows automatically adjust the weight supported by the device, following the values configured in the graphical interface. Additionally, the vertical actuator can be manually activated using an up/down button placed on the Swalker control panel.

C. *Hip coupling mechanism*

This is a steel structure adaptable in height and width to the patient's hip. An orthopedic harness is attached to the structure for the stabilization of the patient's trunk. Two aluminum bar were designed to support both hip sides (left and right). These bars have one degree of freedom moving in the sagittal plane. They are coupled to both thighs with straps and they follow the hip flexo/extension while walking. These rotating movements are transmitted to potentiometers through a belt and pulley system. Using this mechanism, the system accurately captures the flexoextension range during the gait, see Fig. 3 and Fig. 4. A simple calibration process assures high precision in measurements. Both sides incorporate an acquisition board that sends this information to the control unit.

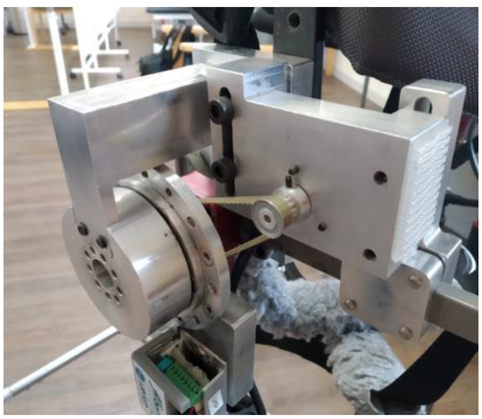

Figure 3. The hip range of motion is measured using two potentiometers located on the robotic structure coupled to the patient's hip

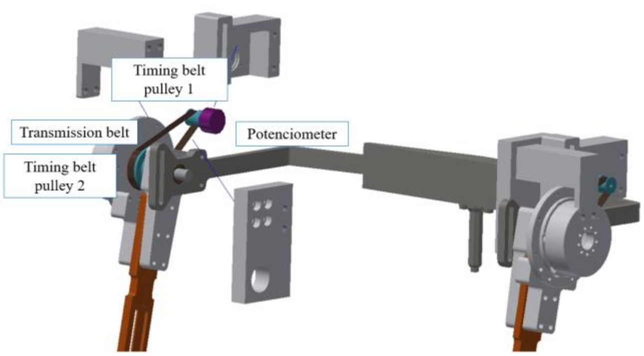

Figure 4. CAD design of the hip coupling mechanism. Mechanical structure and potentiometers for measuring the hip range of motion

IV. CONTROL ARCHITECTURE

The control architecture consists of two modules:

A. *Central control unit*

The main control unit of the system is a PC104, an embedded computer responsible for the execution of the control algorithms and the communication with the different modules (sensors and actuators). The main controllers and the communication protocols are developed using the MATLAB RT environment.

The system incorporates two communication protocols. A CAN protocol (Controller Area Network) is used to communicate the PC104 with the distributed electronics boards to control the actuators and capturing signals from the sensors. An UDP (User Datagram Protocol) bus is used between the PC104 and a Wifi router that enables information transmission between the graphical therapist interface and the control unit, see Fig. 5.

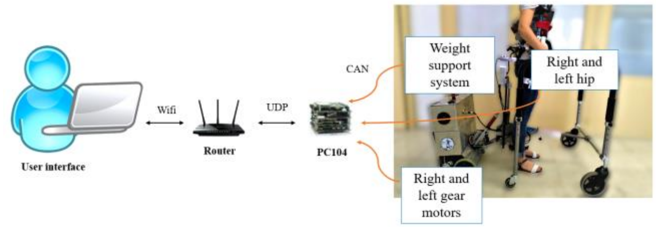

Figure 5. Communication and data transmission scheme

B. *Graphical user interface (GUI)*

A software application running on a Windows tablet was developed to configure the SWalker parameters, mainly the speed and the percentage of weight supported. Additionally, the interface shows the parameters measured, hip range of motion, weight supported and speed while walking. The interface includes three functions: *Patient database*, *New therapy* and *Data analysis*:

- Patients database: Record of new patients including personal data and anthropometric parameters. A SQL server database was implemented. Searching patients, exploring historical data and editing user's profiles are the available functions.
- New therapy: Configuration of a new rehabilitation session. After introducing the percentage of patient's weight supported by the platform, the therapist must select the walking mode. Fig. 6 illustrates the flow diagram of the operating modules.

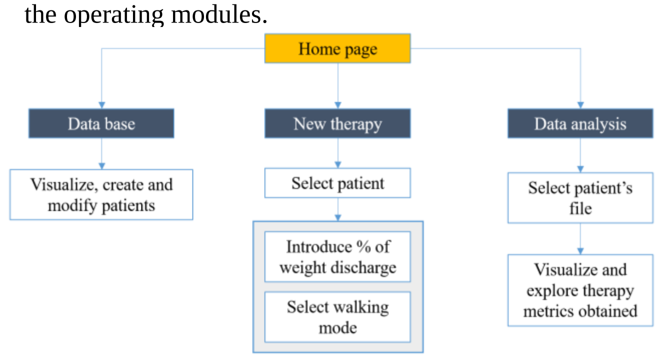

Figure 6. Flow diagram of the operating modules

There are two walking modes: *guided walking* and *free walking*. Both of them move the robot at the set speed. The difference between these two performance modes lies in the robot's start-stop operation. In the first case, the start, stop and direction of the movement is controlled by the clinician using the graphical interface. In the second case, the patient's intention starts and stops the movement of the robot. User's intention is estimated from the flexo/extension angle of the hip. Fig. 7 illustrates both walking modes.

- Data analysis: Visualization of the results. This screen shows the range of motion, the weight discharged and the speed during therapy, versus time. Fig. 8 depicts an example of the visualization of the hip range of motion graph during a test. The green curve represents the degrees of movement achieved by the left hip and moreover, the graph incorporates two-colored configurable stripes to indicate the maximum and minimum normal ranges that a healthy subject should reach.

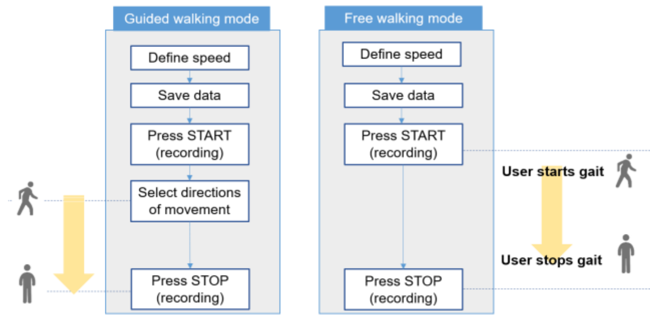

Figure 7. Flow diagram of the walking modes: guided and free walking

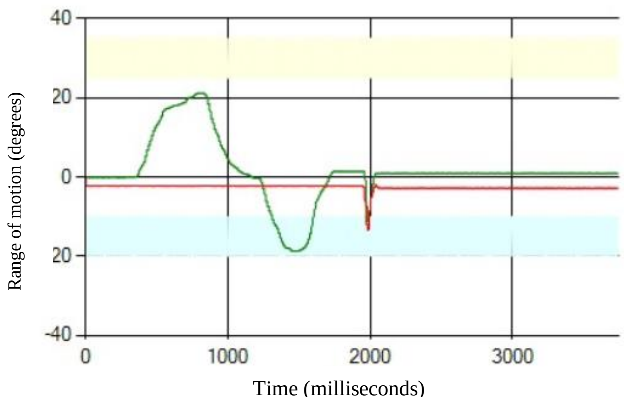

Figure 8. Range of motion of the left hip flexoextension versus time.

V. TECHNICAL AND FUNCTIONAL VALIDATION

SWalker functional validation aimed to assess several technical and usability aspects to ensure the robotic platform fulfilled the conceptual design. Five healthy elderly patients (age 87.6(6.2)) and two physiotherapists participated. Healthy users have not used robotic devices previously. They usually practice physical exercises with conventional equipment such as pedaling machine or walking with parallels bars supports. They did not present intellectual disability. The tests were carried out in the facilities of Albertia Servicios Sociosanitarios. The session consisted of 30 minutes walking along 25 meters corridor. The number of repetitions depended on the users' gait speed. Before starting the functional test, a guide of use was elaborated. The guide was divided into the following sections:

- General description of the Swalker prototype from a functional perspective.
- Precautions and checks for safety. It included the description of the emergency button, battery state and recharge.
- Recommendations for the transfer procedure from seating (wheelchair) to standing (conventional walker and, then, Swalker). This section contained detailed steps to minimize the time and therapist's effort during the transfer.
- Configuration of the therapy session using the graphical therapist interface. This section included a guide for the therapists to configure weight support, speed and walking mode.
- Recommendations for the transfer procedure from the SWalker to the wheelchair or conventional walker. This section described the inverse procedure when the session finished.

The transfer procedure was subdivided into two phases: 1) adjustments before transferring patient and 2) procedure for patient's transfer. Before transferring the patient, the guide described steps for: a) adjustments of the parallels bars according to the patient's height and b) adjustment of the coupling mechanism according to the hip width and c) open the access area by extracting the T-shape structure. The parallel bars and the coupling mechanism for hip adjustment were marked with numbers to record the optimum adjustment for every subject. The transfer procedure was also divided into the following steps: a) transfer the patient from the wheelchair to a conventional walker, b) approach the SWalker to the user and place the harness and thigh straps and c) incorporate the T-shape structure. Them, the therapist configured the different parameters of the session.

The "System Usability Scale (SUS)" was used to interview the two therapists about the usability of SWalker. The SUS is a 10-item questionnaire that provides a look at the ease of use of systems. This scale is based on the standard ISO 9241-11. The two therapists who participated in the study fulfilled the questionnaires, which included the following questions. All questions were evaluated from 0 to 4 points, meaning 0 "Strongly disagree" and 5 "Strongly agree". SUS yields a single number representing a composite measure of the overall usability of the system being studied. To calculate the SUS score, firstly, the score contributions from each item is summed:

1. I think that I would like to use this system frequently
2. I found the system unnecessarily complex
3. I thought the system was easy to use
4. I think that I would need the support of a technical person to be able to use this system
5. I found the various functions in this system were well integrated
6. I thought there was too much inconsistency in this system
7. I would imagine that most people would learn to use this system very quickly
8. I found the system very cumbersome to use
9. I felt very confident using the system
10. I needed to learn a lot of things before I could get going with this system.

For items 1,3,5,7 and 9 the score contribution is the scale position minus 1. For items 2,4,6,8 and 10, the contribution is 5 minus the scale position. Then, the sum of the scores is multiplied by 2.5 to obtain the overall value of SU. SUS scores have a range of 0 to 100. According to the "System Usability Scale", the Swalker may be considered a usable system. The SUS scores were 95 and 87.5 for the two therapists who participated in the study. Table I shows the score for each item and therapist.

TABLE I. SYSTEM USABILITY SCALE

Item	1	2	3	4	5	6	7	8	9	10	TOTAL	SUS Score
Therapist1	3	4	4	4	4	4	3	4	4	4	38	95
Therapist2	3	4	3	4	4	4	3	4	3	3	35	87.5

The system was also evaluated by different verification points (identified gradually as *unacceptable*, *approved* and to *be improved)*, while simulating a standardized rehabilitation session introducing a new user, modifying the walking speed and testing the adequacy of the different adjusting parts. The verification point would be unacceptable if some of the five users reported problems or physiotherapists observed lack of safety. It was "to be improved" when some of the five users or therapists suggested some functional improvements. Finally, it was "approved" when the five users and the two physiotherapists considered that the verification point was fulfilled. Information was gathered in Table I and II.

TABLE II. SYSTEM PERFORMANCE VERIFICATION POINTS

System or function	**Subsystem**		
	Verification point	***Approved***	***To be improved***
Start-up	On/off status	X	
	Battery charging	X	
Drive	All direction trajectories	X	
	Speed control	X	
Weight support	Activation and % discharge	X	
Hip support	Motion capture sensors	X	
Electronics	Connections	X	X
	Battery life	X	
Safety	Fuse indicators	X	
	Emergency stop button	X	
	Mechanical adjustment	X	X
	Electrical contact	X	
Software app.	Transmission of data	X	

TABLE III. USABILITY ASPECTS VERIFICATION POINTS

System or function	**Subsystem**		
	Verification point	***Approved***	***To be improved***
Drive	Adapted speed ranges	X	
Hip support	Proper harness and straps	X	
Accessibility	Safety and easy user access	X	X
Comfortability	Prevention of harmful points	X	
	Electromechanical obstacle	X	X
Parallel bars	Height adjustment	X	
Software app. (development)	Editable patients database	X	
	% weight discharge	X	
	Metric visualization module	X	
	Adapted speed ranges	X	
	Data saving option	X	
Software app. (interaction)	Intuitive	X	
	User-friendly	X	
	User manual and protocol	X	X

The whole system operating performance was validated by the engineering team while the usability aspects were assessed by the users and the clinical staff. As it can be seen, all the verification points resulted *approved*. Nevertheless, it is worthy to mention that the transfer procedure might be considerably improved. It was observed that the extraction and reinstallation of the T-shaped structure makes the process slow and can be optimized.

VI. DISCUSSION AND CONCLUSION

This project aimed to present an innovative approach, applying a new robotic device, SWalker, for the rehabilitation of hip fracture in elderly population. Although, robotic devices have been widely applied on the rehabilitation of neuromotor disorders, there is a lack of literature applied to hip fracture rehabilitation.

The system integrates mechanical and electronic modules that enable the physiotherapist to control and implement personalized rehabilitation. The design of the prototype considered the key aspects in the rehabilitation process of hip fracture. Mainly, creating a safe and usable framework for the patient and promoting the early intervention after fracture by implementing a partial body-weight support system.

Although, a more exhaustive clinical validation must be conducted, this article presented a preliminary technical and functional evaluation. The technical and functional validation consisted of identifying and evaluating the key functions and characteristics of the system. These key verification points were selected to measure how the design requirements were finally fulfilled. Additionally, the therapists fulfilled the "System Usability Scale" with positive results.

All the verification points resulted validated, proving the robotic solution was technically competent and adapted to the target population in a real scenario. Some aspects were registered to be enhanced in a second prototype or before a clinical validation with symptomatic patients. Concretely, the most critical part was the transfer procedure from the wheelchair or conventional walker to the Swalker. A relevant conclusion of this validation is that the system should be more accessible, possibly removing the T-shaped structure initially designed. This issue will be tackled in a second prototype studying how to increase the accessibility without compromising the system stability.

From a technical point of view, the assessment of electric connections and some mechanical set-up showed that there was room for improvements. These aspects referred particularly to the hip support assembly, where the range of motion capture system and the strain gauge connections are closed to the user. The development of a plastic casing covering such areas and wire guides would isolate these parts completely from users' contact providing them with a greater comfortability.

As future work, it is worthy to mention that the development, the technical and the functional evaluation of the Swalker prototype will be useful to develop a more robust second prototype. Finally, this second prototype will be clinically validated measuring the impact on the rehabilitation process after hip fracture. The clinical protocol will include the measurement of physiological and functional variables during the rehabilitation process such as gait speed, muscle mass, grip work and Barthel index among others.

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